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Evaluation of the Migrating Combustion Chamber (MCC) Engine

by
Mr. K. Mike Miller
Mr. Dorin Morar

Report Date
January 1993

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13. ABSTRACT (*Maximum 200 words*)
The Belvoir Research, Development and Engineering Center (BRDEC) tested three Migrating Combustion Chamber (MCC) engines built by Engine Research Associates (ERA) for Natick RD&E Center. The MCC concept attempts to provide a lightweight, quiet engine having a cool exhaust gas stream. The cool exhaust is attained by capturing additional energy from expansion beyond that achievable in conventional engines by the use of gas porting to multiple expansion chambers; this provides a more efficient engine operation than is otherwise attainable for the configuration.

The testing included determining the engine torque-speed-power characteristics and the Brake Specific Fuel Consumption (BSFC) under a variety of load conditions. Startability and operability were concerns; starting under normal ambient conditions was difficult. All testing was performed using a 10:1 fuel/oil mixture of low lead gasoline with AMZOIL synthetic lubricating oil for two-stroke engines.

The maximum power achieved was 0.25 horsepower at 4,400 rpm. The peak torque observed was 69 oz.-in. at 3,200 rpm. It was not possible to make noise and vibration measurements during the testing cycle, but they appeared to be low. The MCC engines tested had relatively short lives, operating for less than 25 hours. Performance and durability improvements are necessary before this MCC design can be considered as a viable alternative to commercially available two-cycle engines.

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Acknowledgement

We would like to thank our colleagues for their thoughtful comments and assistance in the preparation of the manuscript, particularly Eleanor Raskovich and Robert McKechnie. We are indebted to Mark Poppe for his highly professional work and to Bardell Spence and Jeffrey Brenneman for their efforts during the set-up and testing of the engines.

Section I
BACKGROUND

Belvoir Research, Development and Engineering Center (BRDEC) was tasked by Natick RD&E Center to test and evaluate the Migrating Combustion Chamber (MCC) engine concept as developed by Engine Research Associates (ERA). This evaluation supplements the technology assessment effort undertaken as part of the Individual Soldier Power Front End Analysis. Mr. F.L. Erickson invented the basic MCC engine in 1969 and patented it in 1971. Further development and refinements by Mr. Erickson led to patents in 1982 and 1984, both of which included descriptions of the operational cycle of the engines. The development of the MCC engine in various configurations and sizes continues today with the help of private, industrial, and government funding.

Mr. Erickson envisions that the MCC engine will have an improved thermal efficiency that increases its fuel economy by 25 percent when compared to conventional engines. Other characteristics ascribed to this engine concept are very quiet operation, reduced exhaust gas temperature, low vibration levels, multi-fuel capability, and high power/weight and power/volume ratios.

DESCRIPTION

The MCC engine operates differently than a conventional reciprocating piston engine. In a conventional piston engine, high temperature and pressure exhaust gases are vented following the power stroke while still at relatively high temperatures and pressures. In the MCC engine, the hot gases from the initial explosion are "captured" and expanded further in a secondary chamber. The MCC engine concept attempts to extract more of the energy of the gas using only the combustion/expansion process. A simple mechanism consisting of three simply constructed moving parts (see Figure 1) is used. The moving parts form four chambers of variable volume, an intake chamber, a primary combustion/expansion chamber, a secondary expansion chamber, and an exhaust chamber.

The carburetor introduces the air/fuel mixture into the intake chamber. This mixture is further agitated as it moves to the second chamber for the compression-combustion part of the cycle; this is the only chamber where combustion occurs. After the ignition and combustion processes occur, the hot gas expands, pushing the MCC "piston" through its cycle. This expanding gas is ported to the third chamber, which acts as the secondary expansion chamber, where it gives up more of its energy to the process. The gas is finally eliminated through the fourth chamber, which is the exhaust chamber.

The chambers really work as two pairs; the first and the third chambers work together and the second and the fourth chambers work together. The expansion of the primary combustion/expansion chamber forces exhaust gas out of the exhaust chamber. The expansion of the hot combustion gases formed in the primary combustion/expansion chamber continues in the secondary chamber until the gases reach a pressure close to atmospheric. The expansion of the secondary expansion chamber forces the air/fuel mixture from the intake chamber into the primary combustion/expansion chamber. Gas circulation is controlled by ports and the movement of the "pistons." Figure 2 presents a pressure-volume diagram comparison of the MCC engine versus a conventional engine.

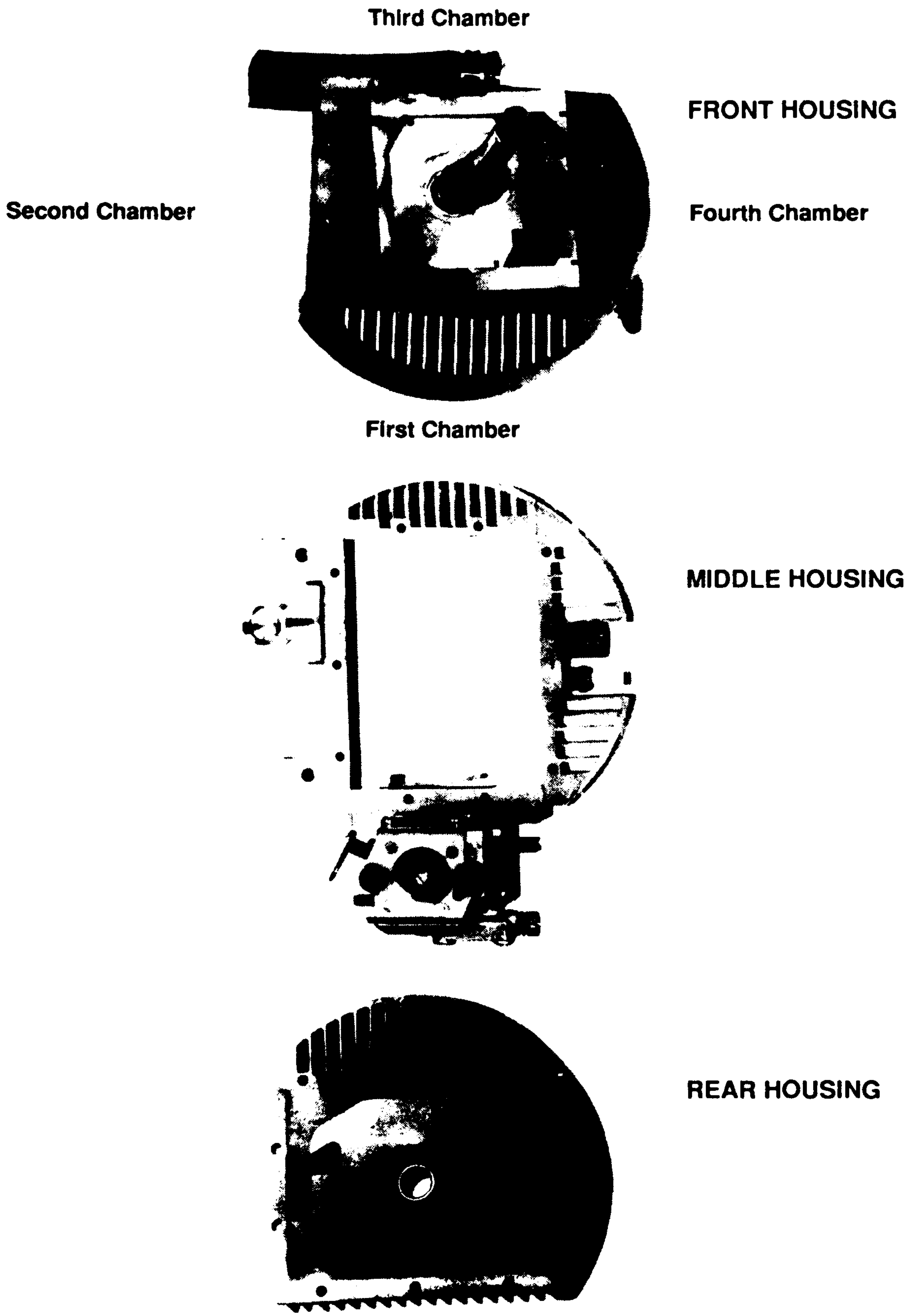

Figure 1. Break Out of MCC Engine

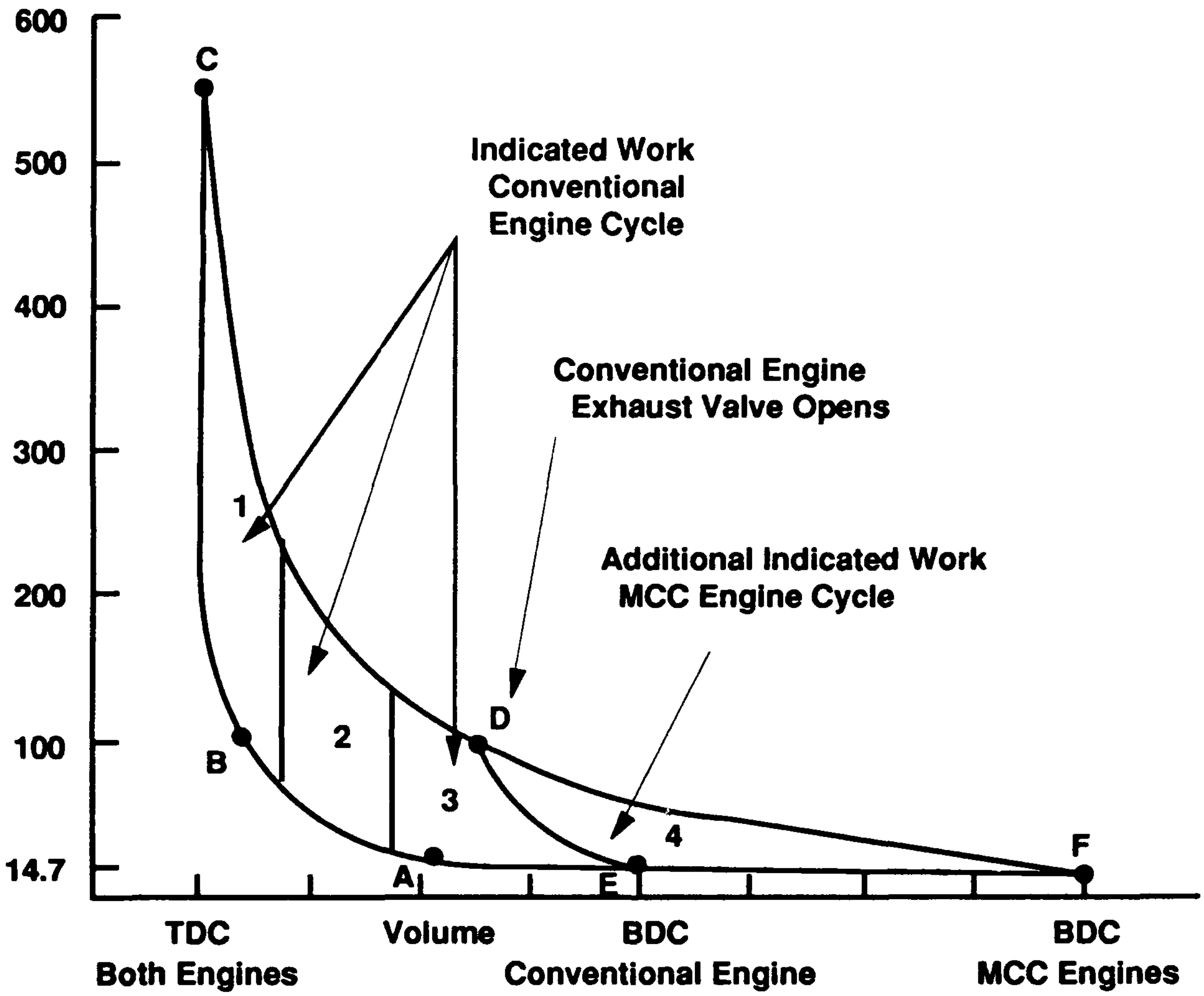

Figure 2. Pressure Volume Diagram Comparison

PHYSICAL CHARACTERISTICS

The engines tested at BRDEC have a displacement of 0.8 cubic inch and a 7:1 compression ratio. The engine and starting mechanism weighs 5.1 pounds, the ignition system weighs 0.3 pound, and an added flywheel weighs 1.4 pounds. The total weight of the assembled unit is 6.8 pounds.

The assembled units are 5.75 inches wide, 5.5 inches high, and 7.0 inches long. No cooling system (fan and/or shroud) was provided. Engine Research Associates rates this engine at 0.4 horsepower when operating at 4,400 revolutions per minute (rpm). Front and back views of an assembled MCC engine are shown in Figures 3 and 4.

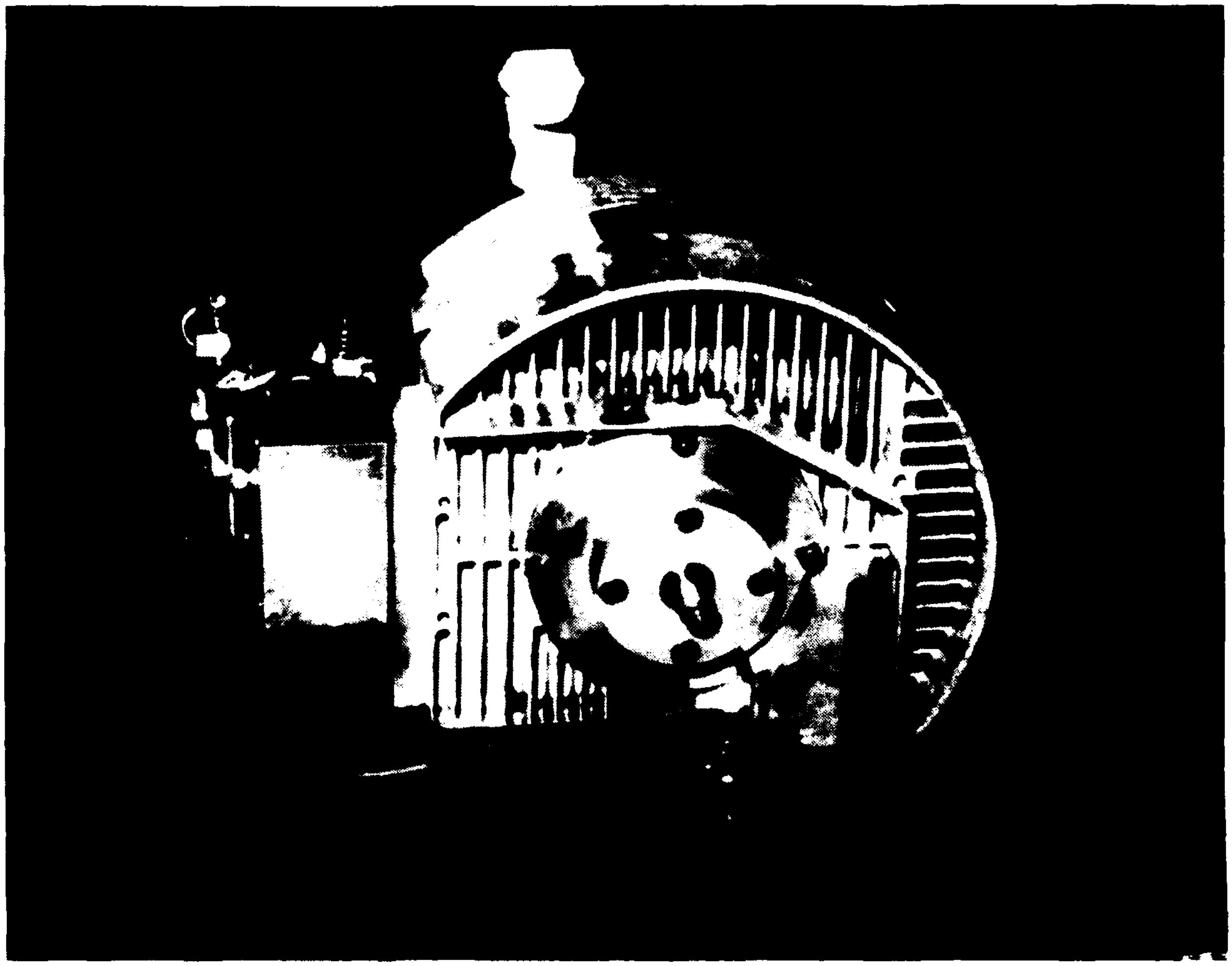

Figure 3. Assembled MCC Engine — Front View

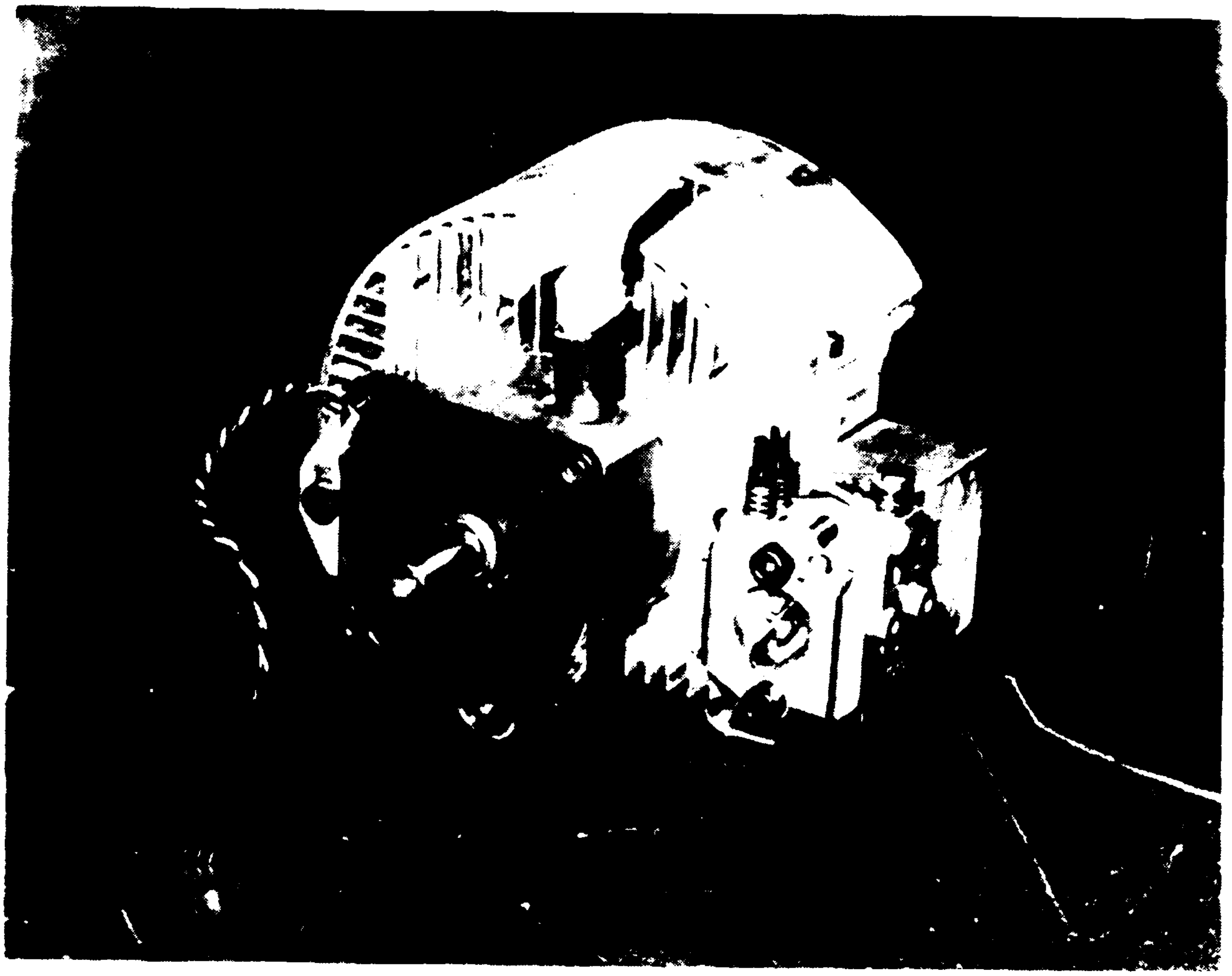

Figure 4. Assembled MCC Engine — Back View

PURPOSE

BRDEC tested and evaluated the migrating combustion chamber engine to independently determine the operability and operating characteristics of this novel engine concept for Natick RD&E Center. An engine which met its inventor's vision would be a competitor for application in the Soldier Individual Power Source development effort. To compare the engine's capabilities with the goals of the development effort, the Test Plan called for a performance test followed by 500 hours of endurance testing.

Section II

DISCUSSION

Information provided to BRDEC to support the MCC engine test included:

1. An SAE Paper written by Mr. Frederick L. Erickson and Mr. George S. Lewis of Engine Research Associates (ERA), Inc., Fort Wayne, IN, describing the unique design of this engine,[1]

2. A paper written by Mr. George S. Lewis presented at Belvoir RD&E Center,[2]

3. A scientific and technical report prepared by ERA Inc. for Natick RD&E Center,[3] and

4. The statements of BRDEC's point of contact at Natick, Mr. John Bartell.

Mr. Bartell recommended that the engine housing temperature not exceed 200°F during operation. This temperature was monitored by a thermocouple placed near the spark plug of the engine. Mr. Bartell further recommended installing a flywheel approximately 3/8 inch thick and 4 inches in diameter (see Figures 5 and 6), not exceeding a speed of 4,500 rpm, and using a fuel/oil mixture of 10:1. All of the testing was done using low lead gasoline and AMZOIL synthetic oil for two stroke engines.

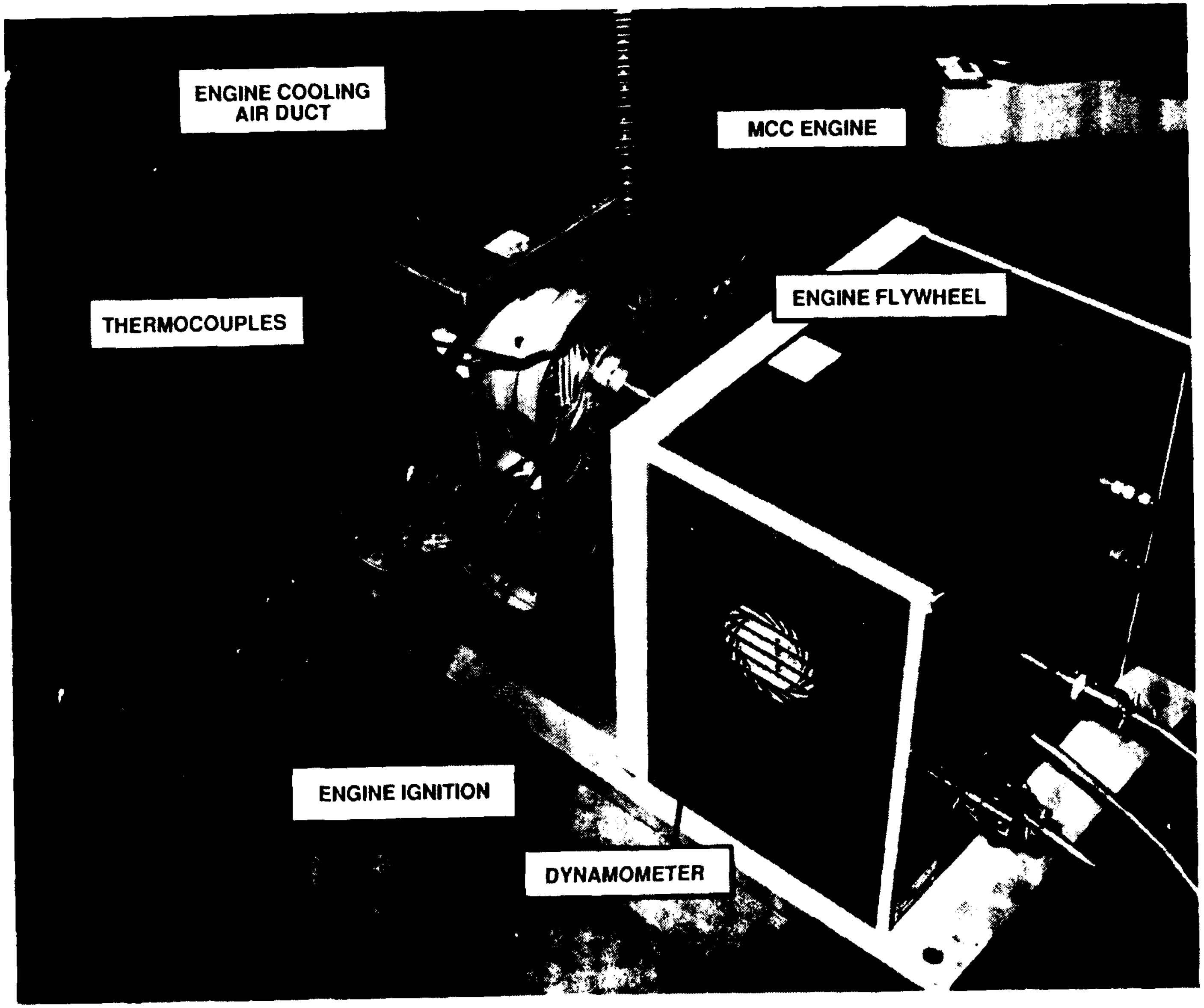

Figure 5. Flywheel Installation and Thermocouples

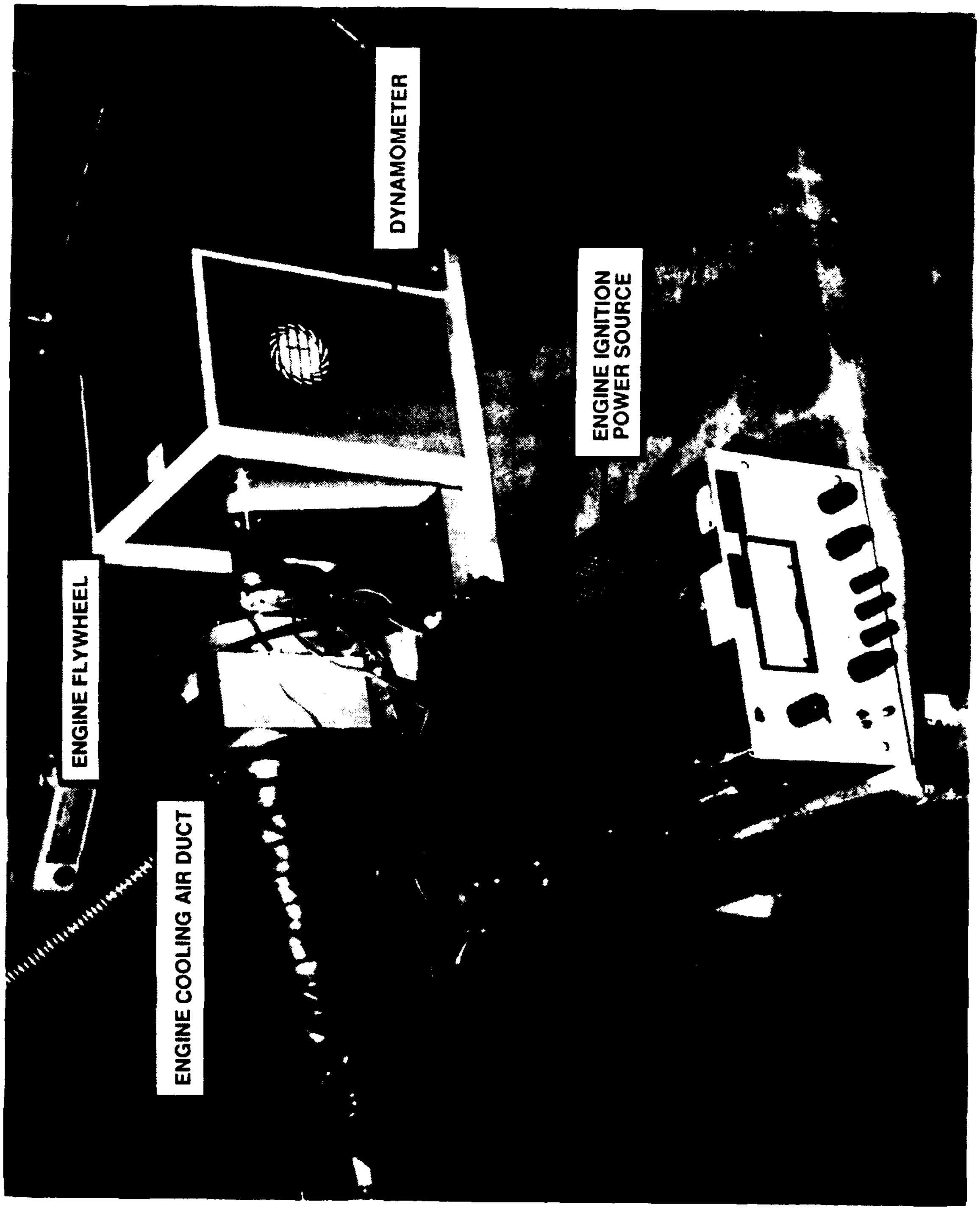

Figure 6. Flywheel Installation

Natick supplied an engine of an earlier design for the initial testing in order to familiarize BRDEC with this new technology. BRDEC was cautioned that this engine was not representative of the performance of units to be shipped later for formal testing because it did not include the latest design and operational improvements. For example, the engine did not have a cooling fan and the starting mechanism was faulty.

To learn the nuances of how this engine operates, a test fixture was designed incorporating a permanent magnet starter/generator with a very low inertia to start the engine. The starter/generator made it possible to electrically spin the engine until it started and then to load it to estimate the engine's performance.

A very powerful fan was connected to a custom-made case that sealed the periphery of the engine housing and ensured the cooling needed to keep engine surface temperatures below 200°F. A thermocouple attached to the engine center housing in the vicinity of the spark-plug continuously monitored the engine temperature (see Figures 5 and 7).

The engine was hard to start at 70°F ambient temperature. Careful coordination between the carburetor choke and throttle was necessary while the engine was spun by the electric starter. Constant carburetor adjustments were necessary to keep this engine running.

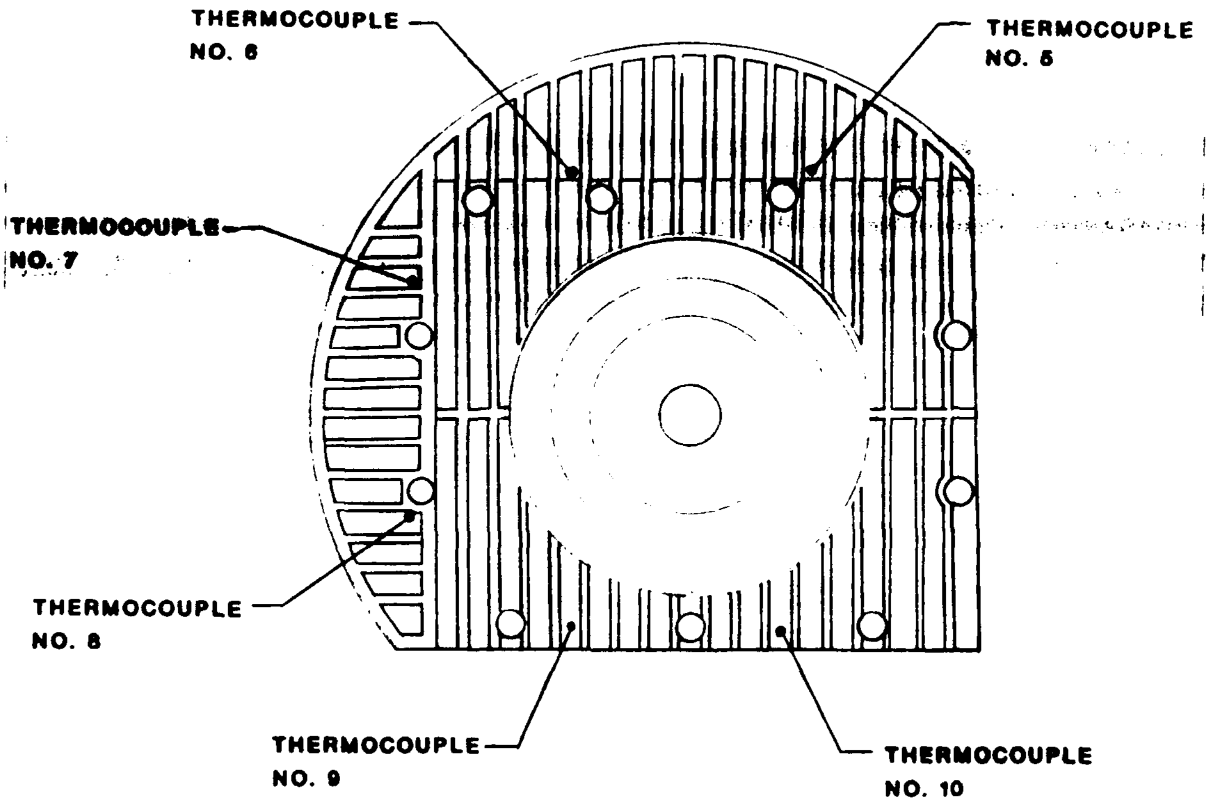

Figure 7. Location of Thermocouples Placed on Housing

Although carburetor adjustments were made, the engine was never able to operate continuously for more than five minutes. Attempts were made to run the engine at temperatures from 200°F to 70°F by using the cooling fan to control the engine temperature, but to no avail. After about 25 minutes of operation, oil started seeping from the engine along the seams where the housings meet. The bolts which secure the housings were examined and found to be tight. The engine was restarted, but it developed a knocking noise and all activities with engine number one were discontinued.

The second engine provided by Natick was used to take actual measurements. The engine was delivered with a starter mechanism but without a cooling fan, so a cooling system similar to the one used for the first unit was fabricated.

A dynamometer-based test set-up was used to perform the testing on the second engine. The apparatus is depicted in Figures 8 and 9; it consisted of the following items:

- MAGTROL Model 4615B Dynamometer
- MAGTROL Model 4629B Dynamometer Controller
- Kurtz Model 505-11-00 air-flow meter
- several thermocouples connected to an OMEGA Model 115KF multiple readout
- OHAUS electronic readout weight scale

Appendix A, "Test Plan for the MCC Engine," lists the test procedures. The parameters monitored during the test were:

- engine speed
- engine shaft torque
- engine shaft power output
- engine fuel consumption
- ambient/intake air temperature
- engine exhaust gas temperature
- engine housing temperature
- engine cooling air flow

The starting procedure was similar to the one used for the first engine. Starting required continuous adjustment of the choke and throttle of the carburetor. However, external pre-heating of the engine housings to about 190°F improved its ability to start.

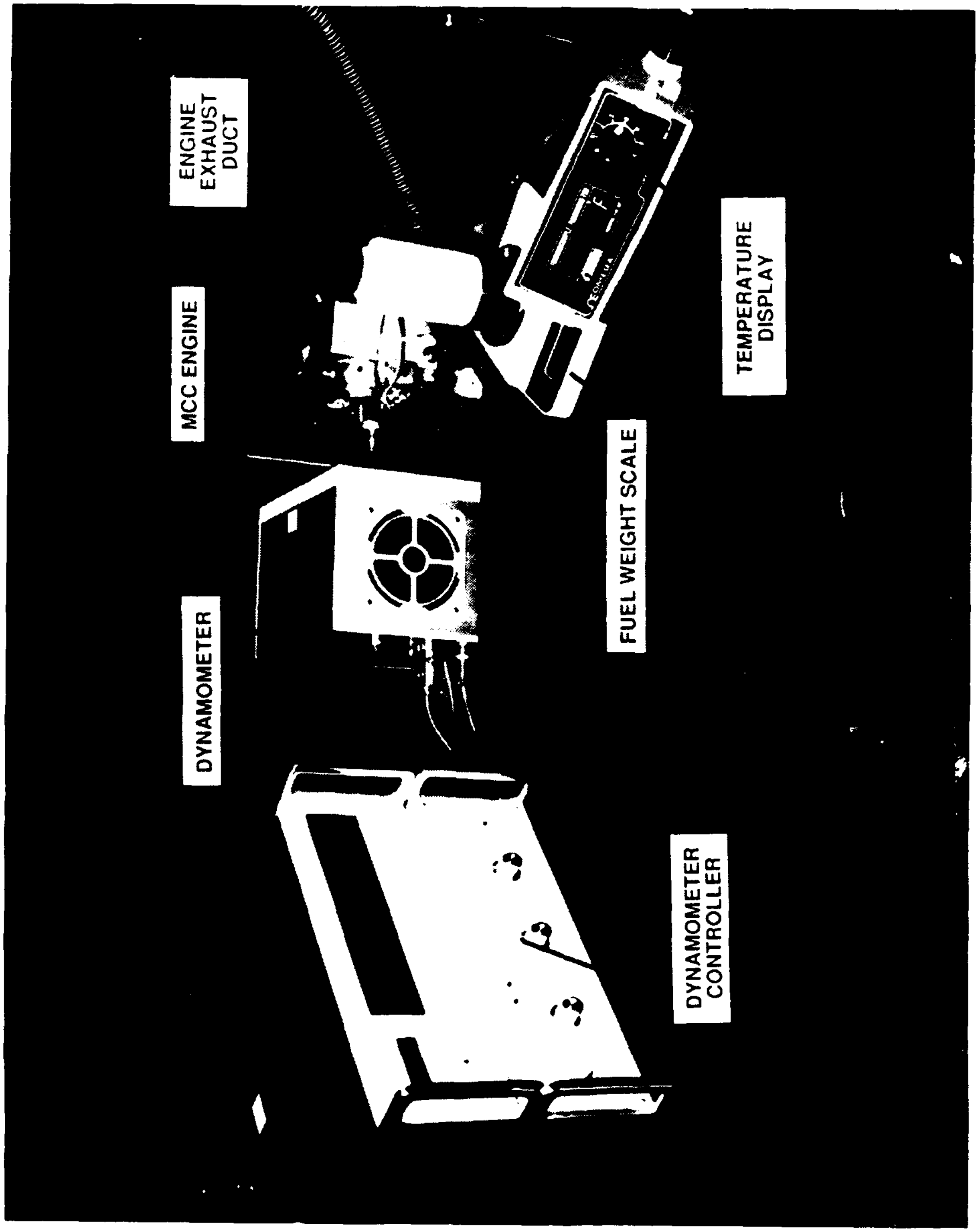

Figure 8. Test Set-Up Measurement Apparatus

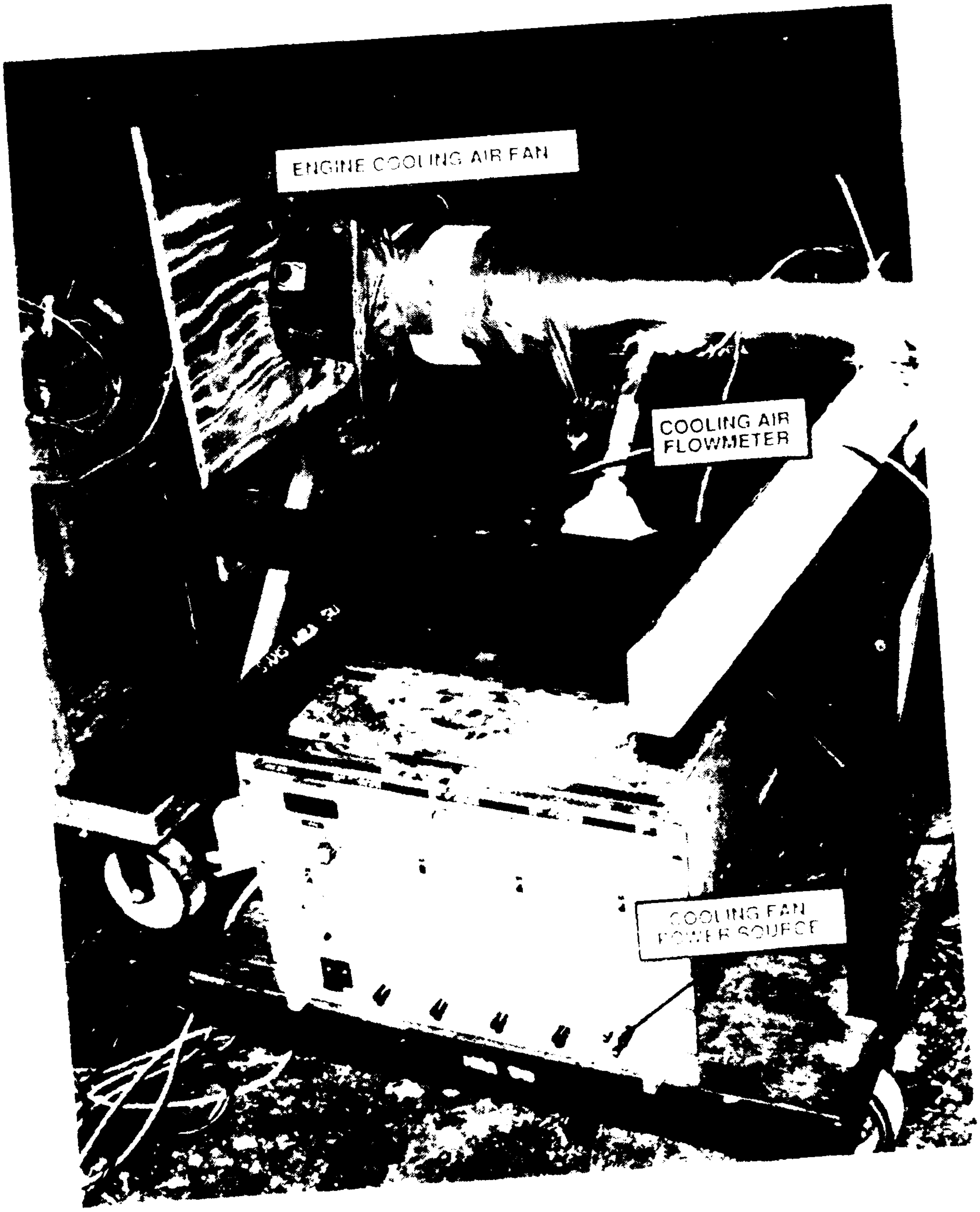

Figure 9. Test Set-Up Cooling Apparatus

During the test, it was found that no one setting of the carburetor ensured a steady engine performance over the desired range of speed (2,500 to 4,500 rpm) and power. While a leaner air/fuel mixture would be beneficial for the specific fuel consumption and for smoother engine running, a much richer mixture was needed to start the engine. The air/fuel ratio was changed by changing the carburetor setting.

The engine was not governed, making it difficult to maintain a steady state operation (constant speed and load) for more than a few minutes. The engine did not accept a measurable load at speeds below 2,500 rpm. Under these circumstances, a limited number of readings were selected for the graphic representation of the power, torque, and fuel consumption vs. engine speed.

The graphic representation of the data taken (see Figure 10) shows that the MCC performance resembles the general profile of any internal combustion engine. However, the MCC engine has less power and torque and greater fuel consumption than a piston engine of similar displacement. The Brake Specific Fuel Consumption (BSFC) of the MCC engine as measured in these tests is about twice that of a comparable power reciprocating engine.

During a test run of this engine, the starting mechanism experienced a failure when its sprag clutch seized on the engine shaft. Brass shavings were found inside of the starter housing on the engine when it was disassembled. Inspection revealed that the sprag clutch/pulley assembly had engaged the brass counterweight located adjacent to it on the shaft. This appears to have been caused by excessive axial play of the crankshaft.

This interference, which occurred while the engine was operating, could explain why the engine was unable to develop the expected horsepower. The brass shavings and continuous rubbing on the counterweight would act as an internal brake, consuming a portion of the power before it was delivered to the dynamometer.

Another intrinsic problem with the MCC engine is the sealing of the "piston" housing. The housing is made up of three parts: a central housing, a front cover, and a back cover. The sealing surfaces are depicted in Figures 11 and 12. Both the first and the second engine leaked oil from their housing seams while operating.

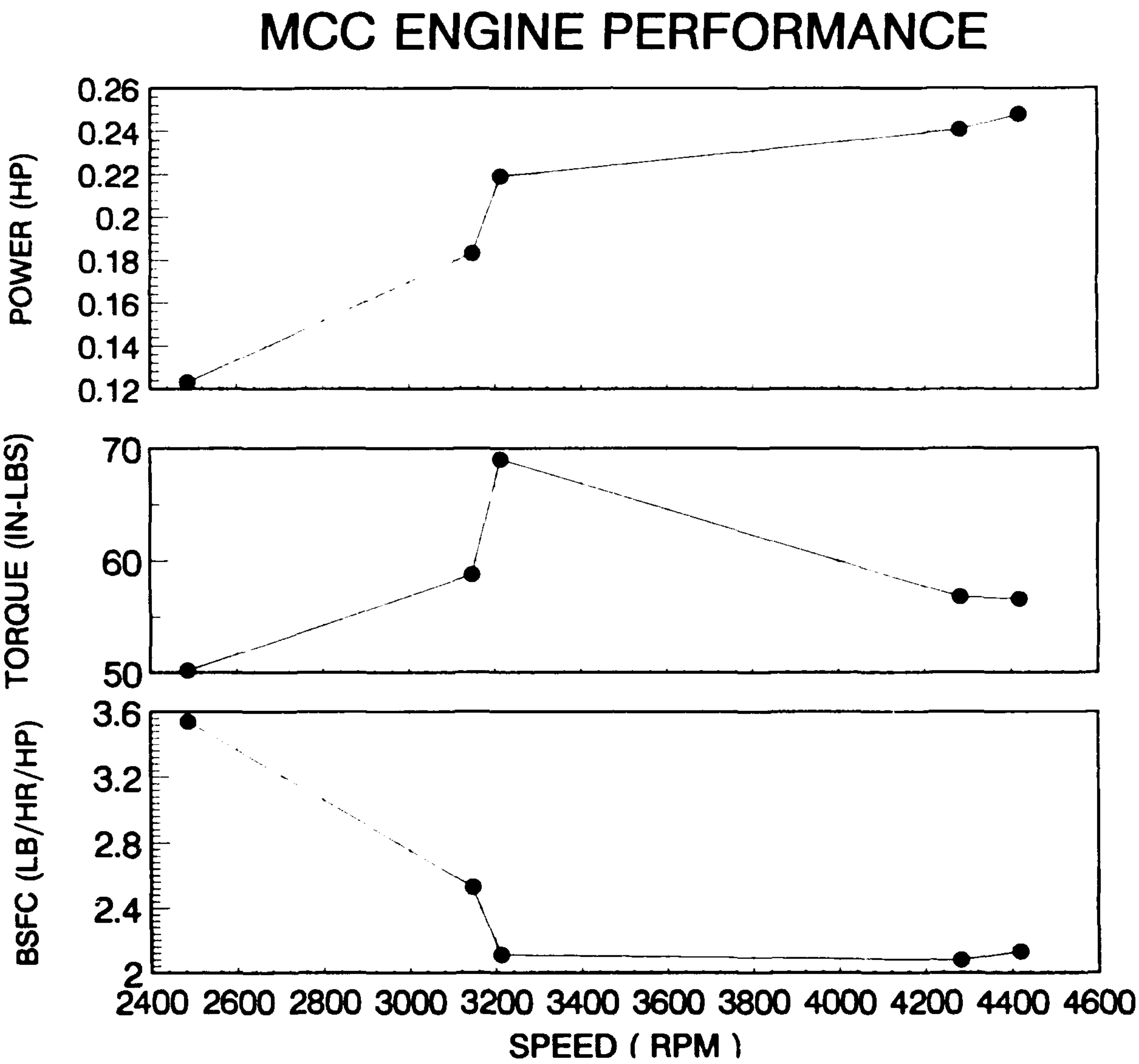

Figure 10. Graphic Presentation of Power, Torque, and BSFC versus Speed

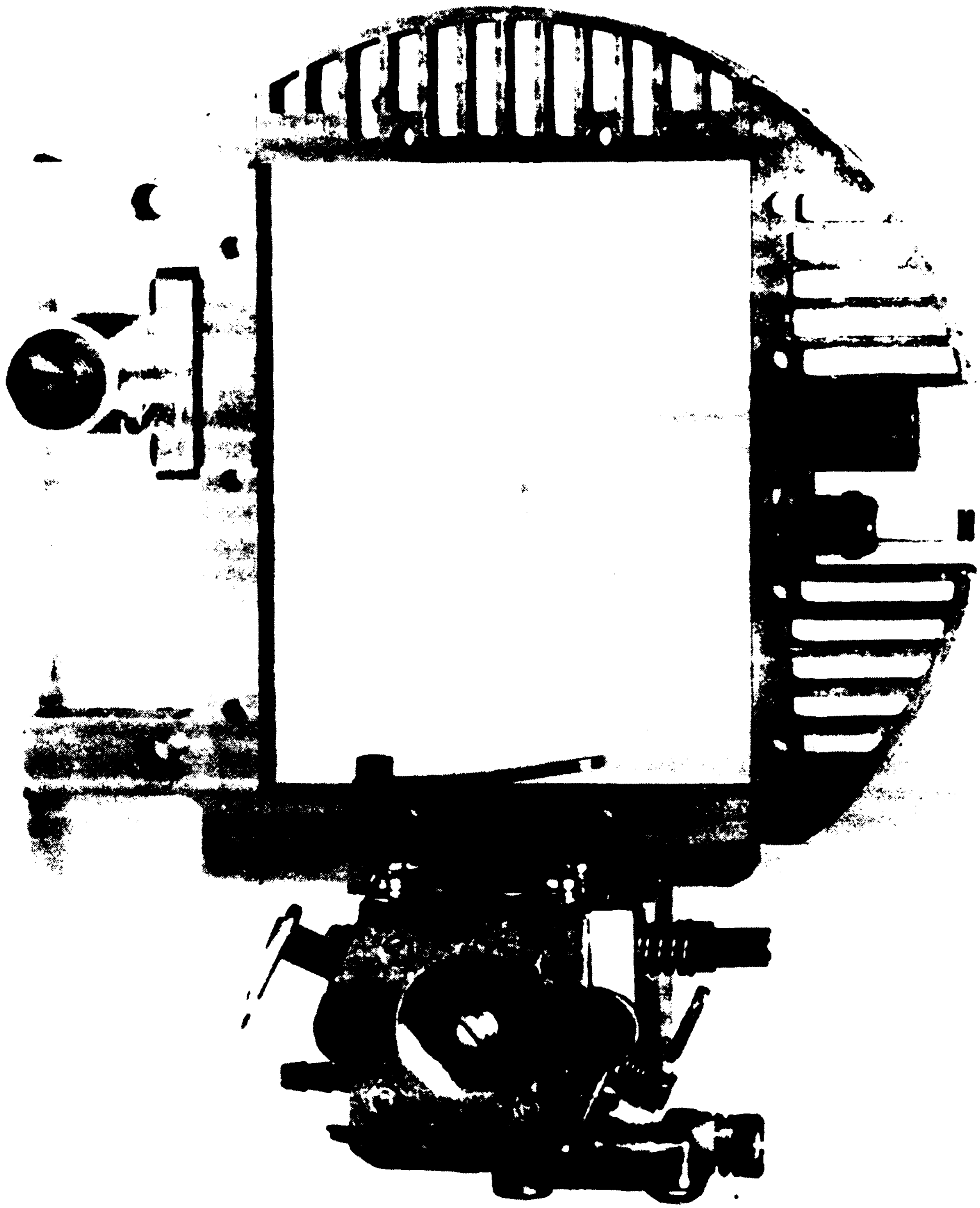

Figure 11. Sealing Surfaces — View 1

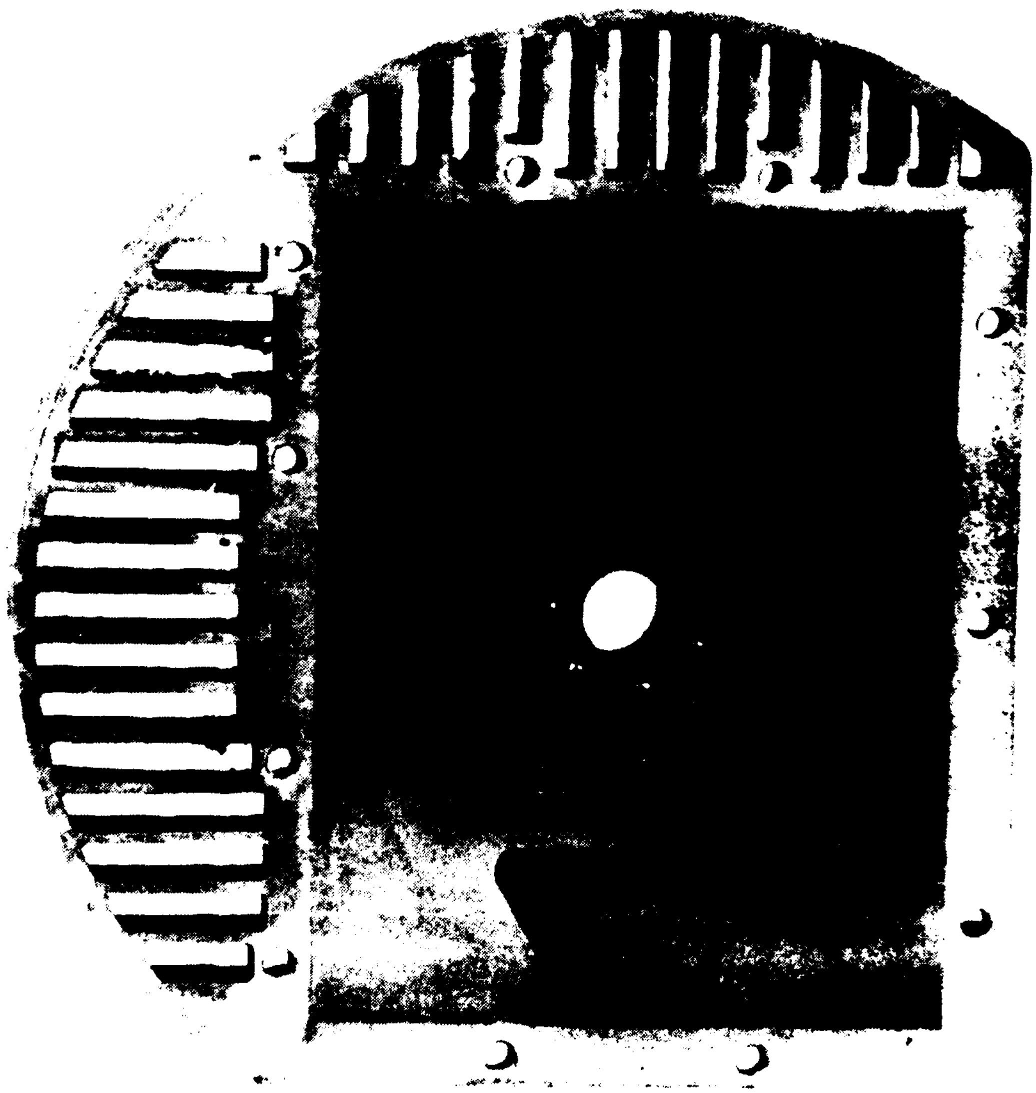

Figure 12. Sealing Surfaces — View 2

Thermocouples were added to the back engine cover in an effort to determine whether or not a temperature gradient existed across the engine. A temperature gradient could cause the housing covers to warp, resulting in an imperfect sealing surface. Subsequent measurements made on the running engine indicated a temperature gradient across the rear face of the engine. Figure 7 shows the locations of the thermocouples. The recorded temperatures are documented in Appendix C, Test Number 05. The lowest temperatures occurred along the side of the engine where the intake charge was introduced. This result would be expected since the air/fuel/oil mixture which is at ambient temperature conditions tends to cool this section of the engine.

The warmest part of the engine was the fourth chamber where the exhaust gases are pumped into the atmosphere. The temperatures demonstrated an average temperature gradient of approximately 50°F from the exhaust chamber to the intake area.

The second engine became increasingly difficult to start as the testing progressed. After two pull starters failed, the second cannibalized from engine number one, modifications were made to the test set-up which made it possible to start the engine with an electric starter motor. The starter motor was momentarily engaged with a coupling on the engine shaft and used to spin the engine. Even with the aid of the starter motor, the engine was unable to sustain operation. Tests on engine number two were concluded.

The third engine was mounted on the dynamometer but was never able to run for more than one minute. Carburetors were switched between the second and third engines to rule out the possibility of a bad carburetor. Switching carburetors did not make the third engine operable. It was noticed that when the engine was spun with the electric starter at speeds of approximately 2,000 rpm, oil leaked from between the center housing and both covers. Bubbles of black oil were blowing out along these seams, indicating a fairly large compression leak. With this observation, testing was concluded.

DISCUSSION OF TEST RESULTS AND OBSERVATIONS

The MCC engines tested produced a maximum of 0.25 horsepower at 4,400 rpm and a peak torque of 69 oz-in (0.22 hp) at 3,200 rpm. This maximum power is 60 percent of the developer's nominal rating for this engine.

The fuel consumption data points were widely scattered. As an aid to understanding the data, sequentially measured values were tabulated (see Table 1) and plotted (see Figure 13). Tracing the sequence of accumulated data points, a learning curve due to refining the adjustment of the carburetor settings is clearly visible. In calculating the conversion efficiency, the energy density of gasoline is taken as 5.53 kilowatt-hours per pound. This value is then reduced by allowing for the approximately 9:1 fuel to oil mass ratio in the mixture, and assuming that no energy is derived from or lost to the oil. For the condition of 0.25 hp delivered while consuming 4.0 grams/minute of fuel-oil mix, the calculated conversion efficiency is 7 percent. This gives a specific fuel mixture consumption of 2.86 pounds per kilowatt-hour. The conversion efficiency for the best performance observed is 7.1 percent.

Table 1. Engine Data

Energy Balance

Data Point Number	Date	Torque (oz-in)	Speed (rpm)	Power (hp)	Air Flow (CFM)	T1 (°F)	T2 (°F)	Delta T(°K)
	23-Aug	1	3470	0.004	165	82	114	17.78
	23-Aug	1	3500	0.003	105	81	127	25.56
	05-Sep	1.6	3100	0	36.5	77	90	7.22
1	05-Sep	1.7	3400	0	86.5	77	93	8.89
2	06-Sep	11.2	4200	0.048		75	105	16.67
	06-Sep	18.4	4500	0.082	103.4	76	110	18.89
	06-Sep	27.2	4500	0.12	103.4	76	119	23.89
3	06-Sep	23.4	4500	0.01	140	77	99	12.22
4	07-Sep	37.6	2600	0.095	78.6	75	122	26.11
5	07-Sep	35	3000	0.1	102	77	122	25.00
6	07-Sep	32	4000	0.122	163	82	125	23.89
7	07-Sep	38.7	4000	0.155	163	82	124	23.33
8	07-Sep	38	4250	0.16	180	85	125	22.22
9	07-Sep	37	4500	0.17	183	86	127	22.78
	13-Sep	1.8	1440	0.002	91	69	93	13.33
10	13-Sep	57	3400	0.191	102	71	115	24.44
11	13-Sep	50.2	2486	0.123	78.5	70	121	28.33
12	13-Sep	58.8	3147	0.183	155	80	119	21.67
13	13-Sep	69	3211	0.219	140	79	120	22.78
14	13-Sep	56.8	4281	0.241	153	78	131	29.44
15	13-Sep	54	3660	0.196	153	80	115	19.44
16	13-Sep	56.6	4418	0.248	161	80	135	30.56
17	13-Sep	48.4	4750	0.228	150	81	142	33.89
	13-Sep	35.2	4750	0.184	150	81	142	33.89
	13-Sep	35	5080	0.22	150	81	140	32.78
18	16-Sep	46	3310	0.145	115	77	91	7.78
	16-Sep	42.6	3309	0.149	101	78	95	9.44
	16-Sep	40.8	3314	0.133	102	78	95	9.44

Energy Balance

Data Point Number	Date	* Q/hour BTU/hr	Fuel Rate (g/min)	lb/kWh	kWh/lb	Fuel Equivalent Power (BTU/hr)	Conversion Efficiency (%)
	23-Aug	5368					
	23-Aug	4911					
	05-Sep	1143					
1	05-Sep	1407	5			11347	0.0
2	06-Sep		6.1	22.5	0.0444	13843	0.9
	06-Sep	3574					
	06-Sep	4520					
3	06-Sep	3131	6	10.23	0.0978	13616	0.2
4	07-Sep	3756	3	5.486	0.1823	6808	3.6
5	07-Sep	4667	4.5	7.676	0.1303	10212	2.5
6	07-Sep	7126	3.7	5.168	0.1935	8397	3.7
7	07-Sep	6960	3.8	4.377	0.2285	8624	4.6
8	07-Sep	7320	3.9	4.324	0.2313	8851	4.6
9	07-Sep	7628	4.6	6.447	0.1551	10439	4.1
	13-Sep	2220					
10	13-Sep	4563	3.5	3.234	0.3092	7943	6.1
11	13-Sep	4070	3.3	4.721	0.2118	7489	4.2
12	13-Sep	6146	3.5	3.374	0.2964	7943	5.9
13	13-Sep	5836	3.5	2.822	0.3544	7943	7.0
14	13-Sep	8244	3.8	2.797	0.3575	8624	7.1
15	13-Sep	5444	4	3.62	0.2762	9078	5.5
16	13-Sep	9003	4	2.861	0.3495	9078	7.0
17	13-Sep	9303	4	3.112	0.3213	9078	6.4
	13-Sep	9303					
	13-Sep	8998					
18	16-Sep	1637	4.1	4.817	0.2076	9304	
	16-Sep	1746					
	16-Sep	1763					

* Heat rejected to cooling airstream

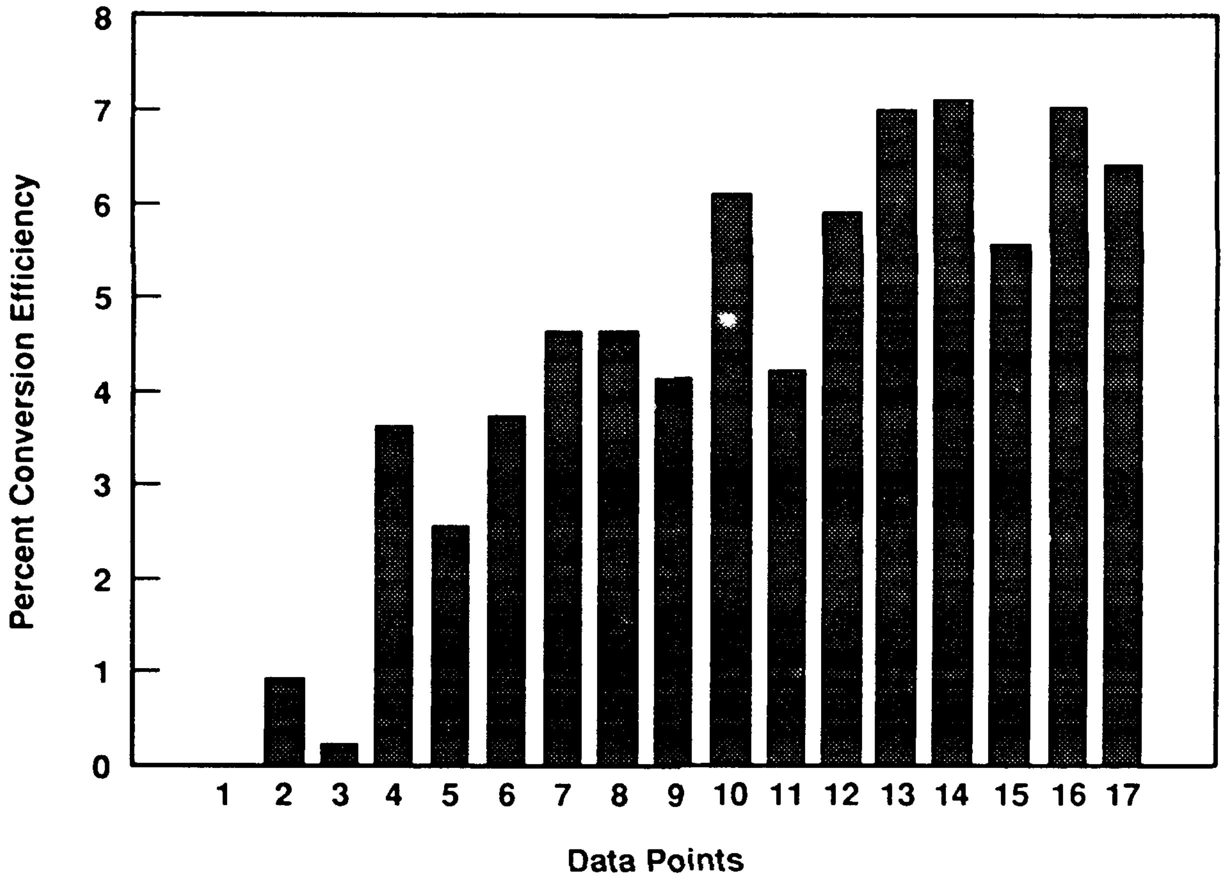

Figure 13. Conversion Efficiency in Chronological Order of Data Taken

In an effort to verify the accuracy of the fuel consumption data acquired in the engine tests, an energy balance was performed. The power output, the heat rejected by the cooling fins to the cooling air stream, and the heat rejected in the exhaust stream were summed and compared to the energy content of the gasoline consumed by the engine. The test apparatus used in these tests did not include a combustion products analyzer, so the assumption was made that the products of combustion included only carbon dioxide, water, and nitrogen. A calculation done on the data which indicated the highest power output showed the following:

Heat Rejection (Cooling Air)	9,003 BTU/HR
Heat Rejection (Exhaust)	470 BTU/HR
Power Output (0.248 HP)	630 BTU/HR
Total	10,103 BTU/HR
Total Energy Input (4.0 g/min)	9,078 BTU/HR

This calculation indicates that the engine rejects 110 percent of the energy available to it. This result is obviously incorrect since it violates the conservation of energy law.

Explanations of the inaccuracy of this result involve the test apparatus. Only one thermocouple was used to measure the temperature of the outgoing cooling air. The temperature of the air should have been averaged over the area of the cooling air outlet. This would have given a more accurate result and helped to pinpoint the areas of the engine where the most heat transfer was occurring. The second problem involves inadequate sealing of the cooling air duct where it was attached to the engine. Any loss of cooling air mass flow occurring downstream of where the mass flow is measured but upstream of the engine cooling fins would result in an artificially high indicated heat transfer. This can be readily seen in the heat transfer equation used to calculate these values: as the mass flow (M) increases the heat transfer (Q) increases, $Q = MCp(T2-T1)$. The other significant possibility of error was in the measurement of fuel consumption. The engine was unable to carry load over a long period of time with stability. This limited the time in which fuel consumption could be measured, and therefore limited the accuracy of the fuel consumption measurement and made achieving thermal equilibrium problematic. The test results are not without merit as the numbers do agree within 10 percent, and any energy/power contribution from burning a portion of the lubricating oil in the mixture is ignored.

Poor thermal performance can be attributed to the large surface to volume ratios of the combustion chamber, poor combustion chamber design, and the possible loss of compression when the engine is running. The combustion chambers of the MCC are generally cylindrical; they have a high surface area from which heat can be transferred and not utilized to make power. The ideal combustion chamber is spherically shaped, the sphere providing the lowest surface/volume ratio, and has a high degree of turbulence or mixing. Part of the problem in these engines may be that the spark plug was recessed approximately one quarter of an inch from the combustion chamber, which could adversely affect the initiation of combustion, especially at low speeds (starting).

The temperature gradient measured across the engine could also have had an effect on the engine performance. Also, the engines leaked oil from the seams in the engine housing. The third engine actually blew bubbles, indicating a loss of compression in the engine. Having cooling fins on the engine adjacent to the combustion chambers and missing from the area adjacent to the exhaust chamber created a temperature gradient. In the tests run with additional thermocouples, the gradient was found to be approximately 50°F. This could be enough of a difference to open engine clearances by 0.001 to 0.002 inch, the clearance tolerance for the engine. The resulting loss of compression would adversely affect the efficiency of the engine.

Although the performance of the small displacement MCC engines evaluated by BRDEC would not qualify the hardware as a candidate for the Individual Power program, the general concept of this engine is very original. The efficient use of the energy from the high pressure and hot exhaust gases, which is wasted in reciprocating engines, would indeed increase the efficiency of this type of engine. However, it is difficult to quantify the amount of resources necessary to optimize the MCC engine. At a minimum some of the key elements which need to be addressed during future redesign and development are the combustion process optimization, engine materials, and engine cooling.

Section III
CONCLUSION

The MCC engine is a creative concept that demonstrates several merits. It is light, weighing about 5 pounds. By observation it seems to have low noise and vibration levels, though no quantitative data was recorded. Its exhaust temperature is lower than other internal combustion engines at comparable power output: an exhaust temperature of 360°F for the MCC engine versus an exhaust temperature of 400°F to 420°F for a two stroke reciprocating engine. An MCC engine with a net output of 0.4 horsepower could be a potential candidate for individual man-portable power sources. It would have to provide the improved fuel energy conversion efficiency that the concept promises and be weight optimized to be considered because its relatively low speed renders it uncompetitive on a power density basis with existing model engines (1-2 hp/lb). It must be emphasized that this engine is a developmental prototype. Various design iterations will be required in order to achieve acceptable levels of performance and longevity. Also, the use of specialized or specially treated materials (such as ceramic coatings and plating of the seals) may be needed to isolate the heat of combustion and decrease frictional losses.

REFERENCES

1. F.L. Erickson and G.S. Lewis, "A Quiet/Cool Exhausting Internal Combustion Engine Using a Highly Efficient, Full-Expansion Operating Cycle," SAE Paper 891792, presented at Small Engine Technology Conference, Milwaukee, Wisconsin, 11-13 September 1989.

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3. F.L. Erickson, J.L. Erickson and B. Richenson, Scientific and Technical Report, Contractor Testing (Contract No. DAAK60-87-C-0046), Prepared for: US Army Natick RD&E Center, Natick, Massachusetts, 13 May 1990.

Appendix A
TEST PLAN

TEST PLAN

FOR

THE EVALUATION OF THE

MIGRATING COMBUSTION CHAMBER ENGINE

DATE

8/20/91

PURPOSE

These tests shall determine the operational characteristics and particular performance of the migrating combustion chamber engine.

SCOPE

One migrating combustion chamber engine shall be subjected to performance testing followed by 500 hours of endurance testing.

PROCEDURE

I. Pretest Engine and Engine Inspection/Preparation

A. Inspection

Review engines' operational/maintenance history and perform a visual inspection for damage. If a potential problem area is noted for a given engine, the engine will be replaced by another provided by the Natick RD&E Center.

B. Preparation

Install the engine on the test bed. Install the flywheel and the flexible coupling between the engine and the dynamometer shafts. Connect the engine to the selected instrumentation and to the cooling installation.

II. Testing

A. Performance testing

Graphs of the engine performance characteristics will be plotted after the completion of the following tests:

1. Maximum power test

A maximum power vs. speed graph will be plotted after taking measurements of maximum power at speeds between 3,000 and 4,500 rpm using 250 rpm increments. All data points will be taken at WOT (Wide Open Throttle).

2. Speed curves

Several power vs. manifold pressure graphs will be plotted after taking data. For each measurement, the speed will be held constant. The set speeds will begin at 3,000 rpm and increase to 4,500 rpm in 250 rpm increments. The manifold pressure increases with an increase in the throttle opening. The power will be measured from the lowest opening of the throttle that allows the engine to run smoothly up to WOT in 0.1 horsepower increments.

Both tests will be performed with the carburetor adjusted for "best power" at 4,500 rpm and WOT and for "best economy" at 4,500 rpm and WOT.

B. Endurance testing

A 500 hour endurance test will be performed after the maximum power test and speed curves performance tests are completed. The following load cycle will be used for the endurance test: One quarter of the test time will be spent at 100 percent of the rated load (0.4 horsepower @ 4,000 rpm); One half of the test time will be spent at 50 percent of the rated load (0.2 horsepower @ 3,000 rpm); One quarter of the test time will be spent at 25 percent of the rated load (0.1 horsepower @ 2,000 rpm).

When the endurance test is concluded another maximum power test will be performed in order to determine whether any measurable degradation occurred.

Appendix B
TABULATED RESULTS

Tests	Engine 1	Engine 2	Engine 3
Max power (hp) test/rating	*	0.25 @ 4400 rpm; 0.40 @ 4000 rpm	**
power demonstrated per pound hp/pound	*	0.036	**
power per volume hp/cubic inch	*	0.3125	**
torque oz-in	*	56.6	**
BSFC @ max power lb/hp-hr	*	2.15	**

* *Engine 1 was used for practice runs only*

** *Engine 3 did not run well enough to get data; failed due to excessive seal leakage*

Appendix C

MIGRATING COMBUSION CHAMBER ENGINE DATA

MIGRATING COMBUSTION CHAMBER ENGINE TEST DATA

TEST NUMBER : 01 DATE: 8/23/91

[illegible] UNLEADED

ENGINE: 1 TEST PERFORMED BY: Miller

RPM, Torque, and Power were measured on the MAGTROL Model 4615B Dynamometer

TIME	RPM	TORQUE oz-in	POWER hp	COOLING AIR CFM	TEMPERATURE F 1 cooling air in	2 cooling air	3 head	4 exhaust	5 combution air in
1014	3470	1.0	.004	165	82	114	135	298	81
1017	3500	1.0	.003	105	81	137	156	263	81
		TEST STOPPED ENGINE DIED WITH ≈ .1 hp LOAD							
Restarted engine 3 times in effort to make it accept load with									
NO LUCK. MAYBE THAT HEAD TEMP IS TOO LOW. WILL ADD COOLING TO									
MAINTAIN HEAD TEMP ≈ 250°F.									
1500	Engine would not restart								
TRIED FOR 2 HOURS TO START ENGINE. Broke starter cord & repaired.									
	Discovered cracked spark plug. TRIED TO FIX with Epoxy. Will									
	look for new plug.								

8/26

[illegible signature] 8/23/91

MIGRATING COMBUSTION CHAMBER ENGINE TEST DATA

TEST NUMBER : 002 DATE: 9/5/91

ENGINE: 1 TEST PERFORMED BY: Miller Moran

RPM, Torque, and Power were measured on the MAGTROL Model 4615B Dynamometer

TIME	RPM	TORQUE oz-in	POWER hp	COOLING AIR CFM	TEMPERATURE F 1 cooling air in	2 cooling air	3 head	4 exhaust	5 combution air in
1425		STARTED ENGINE							
1340		STARTED ENGINE AND TUNED LOW SPEED MIXTURE SCREW ON CARB. ENGINE IDLED AT 2600 RPM.							
1405		RESTARTED ENGINE AFTER CARB ADJUSTMENT TO RICHEN MIXTURE.							
1407	3100	1.6	0.0	86.5	77	90	155	236	84
1410	3400	1.2	0.0	86.5	77	93	162	237	84
	Killed Engine on load application								
1430	Restart								
1431	Checked Dyno operation got .1 Hp								
0500	STARTED ENGINE FOR ADDITIONAL CARB TUNING. ENGINE ACCEPTED .05 Hp LOADS Demonstrated ≈260 EXHAUST TEMPS. BURNED 150 cc of Fuel.								
1345	START ENGINE								
1413	4200	11.2	.048		075	105	165	308	98
1415	4500	~~11.5~~ 18.4	.082	105.4	76	110	200	317	103
'	4500	27.2	.120	105.4	76	119	230	360	104
	ENGINE DIED UNDER LOAD								
1421	4500	Restart		140.00					
1423		NOTICIBLE OIL LEAKAGE ONTO COOLING FINS DOWNSTREAM OF SPARK PLUG.							

FUEL (g)

5g/min UNLOADED

9/6/91

6.1g/m

9/5/91

MIGRATING COMBUSTION CHAMBER ENGINE TEST DATA

TEST NUMBER : 003 DATE: 9/6/91

ENGINE: 1 TEST PERFORMED BY: Miller

RPM, Torque, and Power were measured on the MAGTROL Model 4615B Dynamometer

TIME	RPM	TORQUE oz-in	POWER hp	COOLING AIR CFM	TEMPERATURE F 1 cooling air in	2 cooling air	3 head	4 exhaust	5 combution air in	
1430	4520	23.4	.010	140.	77	99	179	313	85	6.8/min
1432										
1030	START ENGINE									
1036	2600	37.6	.095	78.6	75	122	182	211	100	3g/min
1040	3000	33.0	.100	102.0	77	123	183	233	89	4.5g/min
	engine died upon application of more load									
1047	Restart									
	killed engine on application of load									
1150	RESTART HEAD temp 80°F NO EXTRA HEAT									
1152										
1157	4000	32.0	.122	163	82	125	181	281	86	3.7g/min *
1201	4000	38.7	.155	163	82	124	182	290	86	3.8g/min
1210	4250	38.0	.160	180	85	125	180	306	85	3.7g/min
1220	4500	37.0	.170	183	86	127	194	342	86	4.6g/min

6/7

[illegible] 9/6/91

MIGRATING COMBUSTION CHAMBER ENGINE TEST DATA

TEST NUMBER : 04 DATE: 9/13/91

ENGINE: / TEST PERFORMED BY: MILLER

RPM, Torque, and Power were measured on the MAGTROL Model 4615B Dynamometer

TIME	RPM	TORQUE oz-in	POWER hp	COOLING AIR CFM	TEMPERATURE F 1 cooling air in	2 cooling air	3 head	4 exhaust	5 combution air in	
0253	STARTED ENGINE		IDLING AT	1450 RPM						
0254	1940	1.8	.002	41	69	63	126	159	76	
0255	2500	Killed	Engine	43						
0810	3000									
08:28	3400	57	.191	102	71	115	181	279	78	3.5g/u
				80	71	119	177	224	82	
08:37	2486	50.2	.123	78.5	70	121	173	219	90	3.3
10:30	3147	58.8	.183	~~80~~ 155	80	119	160	250	80	3.5
10:??	3211	69.0	.219	140	79	120	167	261	80	3.5
	4201	56.8	.241	153	78	131	195	344	83	3.8
10:15	3660	54.0	.196	153	80	115	170	293	85	~~5.7~~ 4.0
	4418	56.6	.248	161	90	135	197	362	83	4.0
	4750	48.4	.228	150	81	142	190	350	72	4.0
	4250	35.2	.184	150	81	142	150	350	72	
	5080	34.0	.220/.170	150	81	140	172	325	68	

Kevin M Miller
9/13/91

MIGRATING COMBUSTION CHAMBER ENGINE TEST DATA

TEST NUMBER: 05 DATE: 9-16-91

ENGINE: 1 TEST PERFORMED BY: Miller

RPM, Torque, and Power were measured on the MAGTROL Model 4615B Dynamometer

TIME	RPM	TORQUE OZ-IN	POWER HP	COOLING AIR CFM	FUEL CONS.	TEMPERATURE °F 1	2	3	4	5	6	7	8	9	10
1600	ENGINE	STARTED	AT 72°F	WARMED TO		78	98	182	103	130	151	142	150	169	160
1602	~~3600~~														
	3300														
1604	START														
1606	3310	46.0	.145	115	.145 oz/min	77	91	281	84	129	163	150	174	208	190
1610	3309	42.6	.149	101		78	95	292	89	139	175	160	185	221	204
1614	3314	40.8	.133	102		78	95	296	89	140	178	162	189	227	211
		ENGINE	STOPPED												

[illegible signature]
9/16/91

TEMPERATURES: 1-COOLING AIR IN, 2-COOLING AIR OUT, 3-EXHAUST, 4-COMBUSTION AIR IN
5-10-ENGINE TEMPERATURES (SEE MAP)

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